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Programs in Renewable Energy

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Geothermal Energy Program Summary

Volume I: Overview

Fiscal Year 1988

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On the Cover — Magma, or molten rock, is a surface indication of the immense heat energy within the earth, which is being tapped by modern geothermal technology. The photo shows magma erupting from the Kilauea Volcano in Hawaii.

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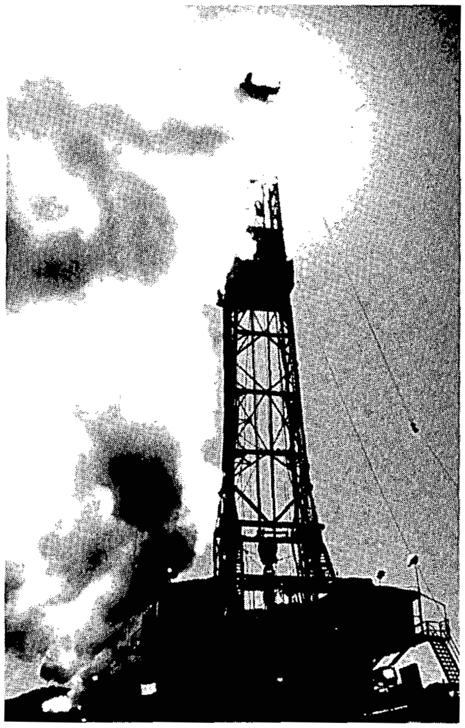

Geothermal Energy Program Summary

Volume I: Overview
Fiscal Year 1988

Geothermal Technology Division

U.S. Department of Energy

Washington, D.C.

Contents

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Introduction

Geothermal energy — the heat of the earth — is one of the most reliable energy sources available. It is also a very large and widespread resource, as shown in Exhibit 1 and Figure 1. The resource is already making a significant contribution to the nation's energy needs — both as heat and electricity — and its future is even more promising.

Exhibit 1
U.S. Geothermal Resources

Total Resource Base[a]		U.S. Accessible Resource Base[b]		U.S. Reserves[c]	
Quads	BBOE[b]	Quads	BBOE[d]	Quads	BBOE[d]
1,505,408	225,910	22,588	3,840	247	42
(42.7% of Total U.S. Energy Resource Base)		(4.4% of Total U.S. Accessible Energy Resource Base)		(3.8% of Total U.S. Energy Reserves)	

a The total resource as specified in United States Geological Survey (USGS) Circular 790, but modified by the National Academy of Sciences to include resources within 6 kilometers of the surface and with a heat value > 80°C (except for hydrothermal, which is > 40°C). Geopressured resources are included to a depth of 7 kilometers.

b The accessible resource as specified in USGS Circular 790, but modified by the National Academy of Sciences to include only accessible resources within 6 kilometers of the surface and > 80°C, except for hydrothermal resources which are > 40°C. Geopressured resources to a depth of 7 kilometers are also included.

c The reserves as specified in USGS Circular 790, but modified by the NAS. In addition, low temperature (<90°C) hydrothermal 30-year resources from USGS Circular 892 are added to the total.

d Billion barrels of oil equivalent.

Geothermal energy originates from the earth's molten interior and the decay of radioactive materials in the crust. In some places, this heat comes to the surface in natural streams of hot water or steam, which have been used since prehistoric times for cooking and bathing. Man-made wells convey the heat from deep in the earth to homes, farms, factories, and electric generators.

As shown in Exhibit 2, there are four categories of geothermal energy, which vary in character according to the form in which they occur. These differences necessitate the variations in production technologies described in Exhibit 2; they also dictate the uses to which geothermal energy can be applied economically. All forms of the resource are potentially capable of electric power generation if sufficient heat at a high enough temperature can be obtained for economic operation. However, the power conversion

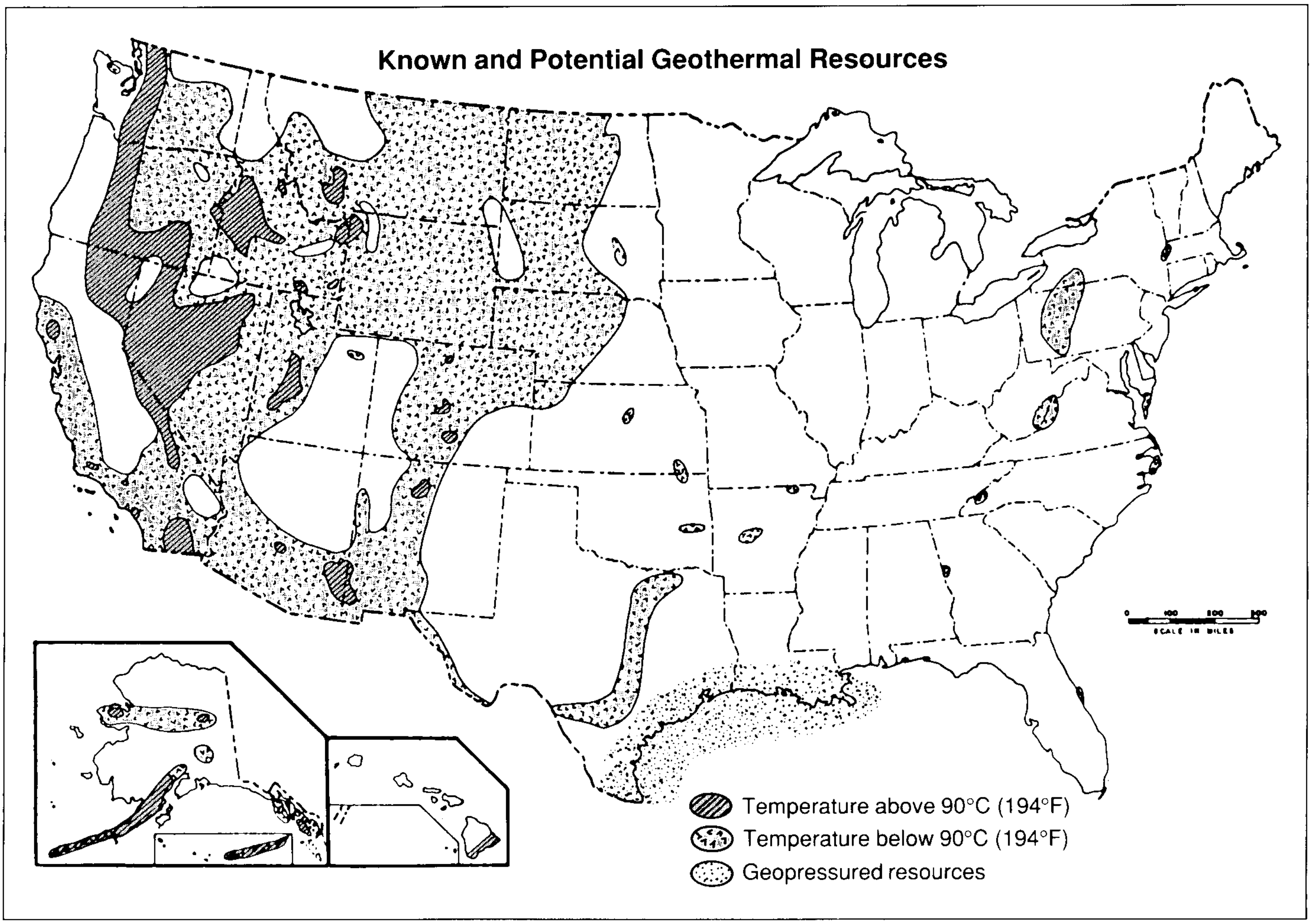


Figure 1. Geothermal resources in the United States.

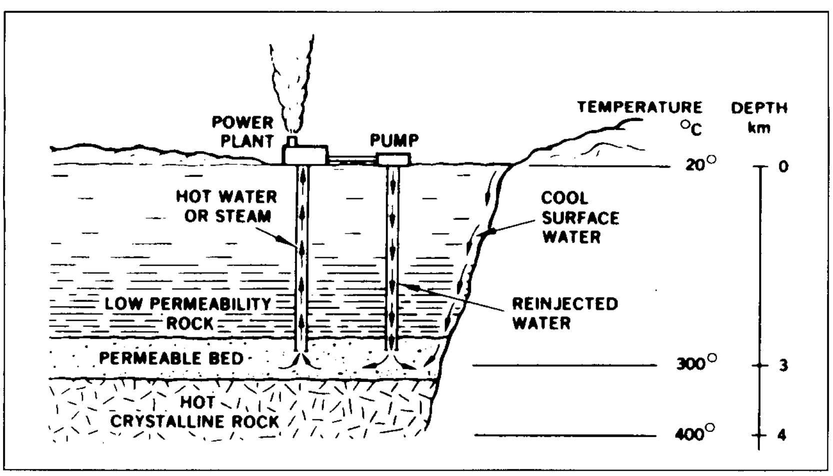


Figure 2. Typical hydrothermal system.

technologies employed vary according to the form and temperature range of the resource. The heat of the resources that are not commercially exploitable for this purpose — those with temperatures below about 150°C (300°F) — can be used directly for space heating and cooling, commercial greenhouses, fish hatcheries, and industrial processes.

To date, all commercial development of geothermal energy — both for power generation and direct use — has employed the hydrothermal resource, which is illustrated in Figure 2. The advanced technology needed for economically extracting the heat or other forms of energy from geopressured brines, hot dry rock, and magma is under development.

Exhibit 2
Characteristics of Four Categories of Geothermal Resources and Methods of Energy Extraction

Type of Reservoir	Form of Energy	Typical Depth (feet)	Temperature Range (°F)	Method of Energy Extraction
Hydrothermal	Hot water and/or steam	Several hundred to 14,000	90->680	Conventional oil and gas rotary drilling equipment modified to withstand heat, hard rock, and corrosive geothermal environment.
Geopressured	Moderately hot water under high pressure containing dissolved methane	10,000-20,000	212->400	High pressure oil and gas rotary drilling equipment and gas-liquid separators to extract methane from the produced brines.
Hot Dry Rock	Relatively water-free hot rock	8,000-20,000	Highly variable	Closed-loop circulation of water through man-made fractures in hot, impermeable rock between two directionally drilled wells.
Magma	Molten or partially molten rock	10,000-33,000	1650-2200	Experimental drilling system that will chill, solidify, and fracture magma through which a working fluid will be circulated for direct contact heat transfer.

Resource and Technology Overview

The Resources

Hydrothermal

Hydrothermal systems can be categorized as liquid-dominated (hot water) or vapor-dominated (steam) based on the dominant fluid phase trapped in fractured and porous rock. The temperatures for electric power production range from 150°-360°C (300°-680°F) with the most useful temperatures in the upper end of the range. The highest quality U.S. resource areas are located in the western states, where relatively young volcanoes or a thinning of the earth's crust are associated with many shallow high-temperature sites. A large number of low-temperature systems — <90°C (194°F) — are also found in the West as well as in the eastern and central United States.

Geopressured-Geothermal

Geopressured brines, fluids containing dissolved methane at moderately high temperatures, are at near normal hydrostatic pressure (0.5 psi/ft) at shallow depth in permeable sandstone. However, when these permeable zones are sealed off at depth by an impermeable layer, the brines in shale and sand-stone formations below are under pressures far greater than normal (approaching 1.0 psi/ft). The best known geopressured resource base lies along the Texas and Louisiana Gulf Coast, although similar conditions may exist elsewhere in the United States.

Hot Dry Rock

In order to bring the heat of water-deficient rock to the surface, an artificial or man-made reservoir must be created. Water is injected down one well, circulated through the hot rock, and recovered through a production well. The most accessible hot dry rock systems of sufficient temperature to produce electricity are found mostly in the western states in young volcanic centers, which may also contain hydrothermal reservoirs.

Magma

This type of geothermal energy is contained in molten or partially molten rock at accessible depths in the earth's crust. As shown in Exhibit 2, magma is extremely hot, which will make it possible to use the heat at high thermodynamic efficiency. Accessible magma is limited to volcanic regions in the West.

Extraction Technologies

Successful extraction of geothermal energy requires both drilling and the application of the geosciences — geology, geophysics, and geochemistry. These technologies are used at every stage of geothermal development — exploration, resource confirmation and characterization, and field management.

Geosciences

The geosciences are used prior to drilling to characterize subsurface properties and to optimize placement of production wells and wells used to inject spent fluid back to the subsurface. In hydrothermal application, conceptual geological models define the geometry and physical properties of the reservoir, geochemical models analyze changes in reservoir fluids and rocks, and numerical simulation predicts long-term reservoir behavior. Nonhydrothermal types of geothermal energy have special technical geoscience requirements.

Drilling

Subsurface assessments are followed by exploratory drilling, production testing, and production of the resource for use. The surface appearance of the drilling equipment used is familiar to all who have observed oil and gas field operations. However, the technical modifications identified in Exhibit 2 are required for each of the geothermal resource categories.

Hydrothermal wells may be produced by allowing artesian flow — fluid forced to the surface by underground pressure — or may be pumped to retain the fluid in liquid form. The choice depends on the particular utilization technology selected.

Utilization Technologies

The energy contained in all four categories of geothermal resources may potentially be used to generate power or to provide heat for direct applications.

Power Generation

Three discrete energy conversion technologies may be used for generating electricity with geothermal resources. The resource characteristics that dictate the use of a particular technology are the form in which it occurs (vapor or liquid), its temperature, and its chemistry.

Conventional turbine generators of standard materials are employed with naturally occurring dry steam. There is no significant difference between this type of operation and conventional power generation except that the natural steam, which is used as it comes from the earth, replaces the boiler. However, once the steam is condensed, gaseous and solid impurities become more concentrated and the condensate becomes more corrosive. Thus, more expensive materials, such as stainless steel, are needed to protect subsequent system components. In addition, at The Geysers steam field in California, the largest geothermal complex in the world, abatement systems are mandated by state air pollution standards. These systems reduce the ambient levels of hydrogen sulfide, an odorous noncondensible gas entrained in the steam. Despite these requirements, geothermal steam is one of the most cost-effective "fuels" for electric power production. According to the president of Pacific Gas and Electric Company, the major utility at The Geysers, "Geothermal is second only to hydro as the cheapest source of energy in the PG&E system."

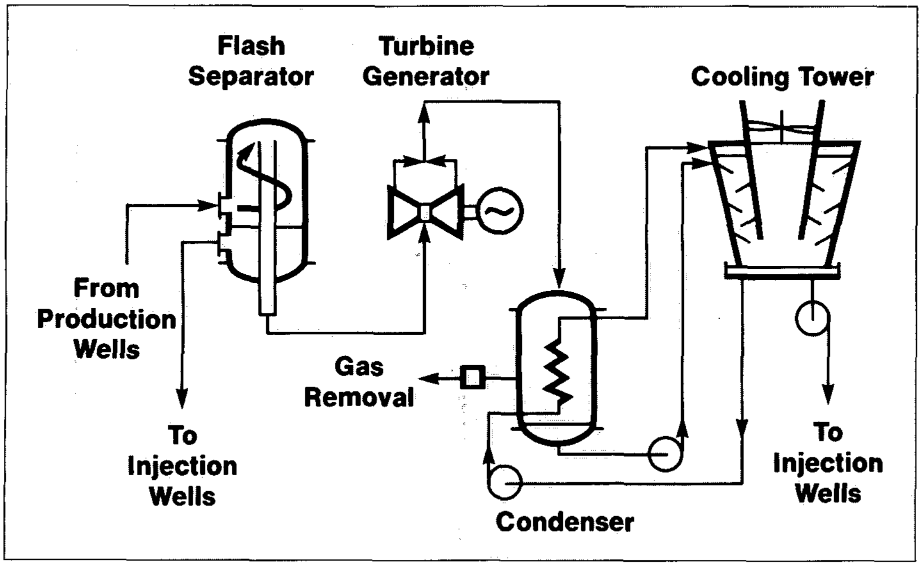


Figure 3. Flash steam technology.

When the temperature of liquid geothermal resources is 200°C (400°F) or higher, flash steam technology, illustrated in Figure 3, may be employed. This term derives from the fact that the liquid is allowed to flash to steam under reduced pressure as it reaches the ground surface. The steam is separated from the remaining liquid and used to drive a turbine generator. Because corrosive, noncondensible gases are liberated in the flashing process and high levels of dissolved solids may be present in the liquid, the materials used and the design of the system become critical in eliminating scaling and corrosion problems. Such problems can interfere with the economic operation of a plant; if severe enough, they could cause the plant to be shut down. Thus, flash plants are not as economically attractive as those of the dry steam variety, but still are competitive with conventional power generation when the geothermal resource is hot enough. Today, the economics of most geothermal flash plants in operation or under design are improved by using a dual flash cycle, which can produce as much as 20%-30% more power than a single flash system at the same fluid flow rate. It is anticipated that the application of flash steam technology will be limited to high-temperature hydrothermal liquid-dominated (hot water) reservoirs, and potentially, water heated by hot dry rock and magma operations. The temperature of these operations may be quite high in some areas.

Lower temperature hydrothermal liquids and geopressured brines are more suited to binary cycle units, shown in Figure 4. These units may be used to generate electricity with temperatures in the 150°-200°C (300°-400°F) range, or lower if very small units are employed. In this technology, the heat

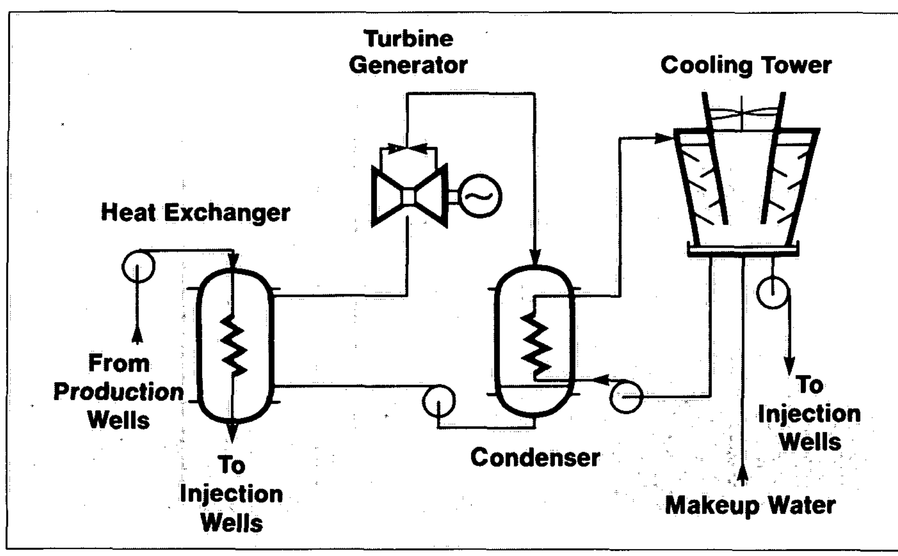


Figure 4. Binary technology.

of the geothermal liquid vaporizes a secondary working fluid for use in the turbine. A number of binary plants are in operation in the United States, ranging in size from units of less than 1 megawatt-electric (MW_e) to 30 MW_e. The large capacities are made up of multiples of small units — e.g., the 30-MW_e binary plant comprises 26 1.2-MW_e modules. These plants enjoy a number of advantages, such as the ability to continue operation while one or more of the units are off line for servicing.

It is not currently known whether flash or binary technology will be the optimum technology for converting energy extracted from hot dry rock or magma to electricity.

Direct Use

Geothermal resources cooler than 150°C (300°F) usually are not economic for electric power production except in very small units. Such resources (and hotter ones as well) are suitable for applications that require large amounts of heat at or below the resource temperature, such as district heating systems, industrial process heat, and crop drying.

The technology for direct uses is mainly drawn from conventional hot water and steam handling equipment employed in similar applications using heat from sources other than geothermal. For example, a geothermal district heating system will generally have the same components as a conventional system. The geothermal production field, which includes wells, pumps, and collection mains, replaces the boiler in a conventional system. All other components such as piping, valves, controls, and metering would be the same. Other technologies for geothermal direct applications are similarly akin to conventional technology.

The technologies employed in direct applications have matured to the extent that the geothermal research program has discontinued direct involvement. However, the program supports the transfer of direct use technologies to users and potential users through the activities of the Geo-Heat Center at the Oregon Institute of Technology.

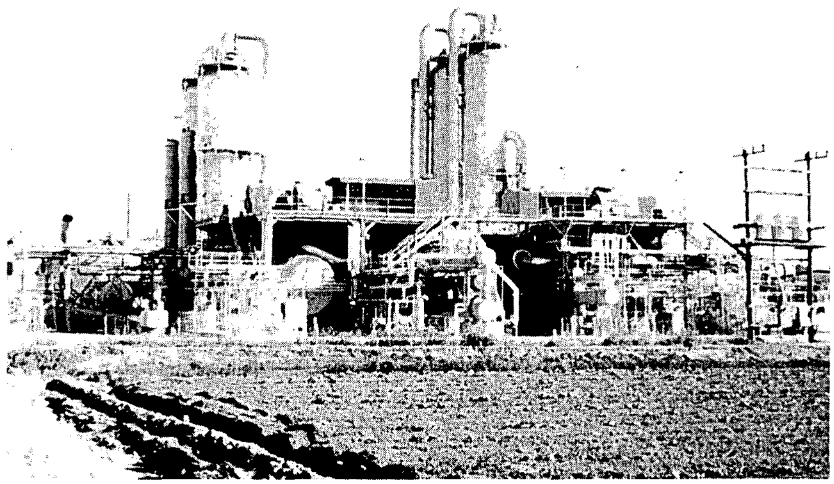
Status of Geothermal Technologies

When the federal Geothermal Energy Research and Development (R&D) Program was initiated in 1971, less than 200 MW_e of dry steam geothermal power generating capacity was in operation at The Geysers, and industry's first hot water demonstration plant was nine years in the future. The brines of some major reservoirs would scale production wells almost shut, corrode and erode turbine blades, and plug injection wells. Geothermal drilling costs were as much as four or five times those of oil and gas drilling, yet drilling was necessary to identify, confirm, and characterize reservoirs in the absence of reliable geoscientific techniques adapted to geothermal conditions. No research into energy extraction from geopressured brines, hot dry rock, or magma had been conducted.

Today, as the twentieth anniversary of the program approaches, considerable progress is evident. At the same time, our understanding of the remaining R&D requirements for exploiting all forms of geothermal energy is much clearer.

Hydrothermal Status

Nearly 2000 MW_e of capacity are on line at The Geysers, and by the end of 1989, some 45 hot water plants are expected to be in operation in six states with a total capacity of nearly 780 MW_e. Much of the hot water development is taking place at the Salton Sea Known Geothermal Resource Area (KGRA)



Magma Power Co. 35-MW_e dual-flash plant on the site of the Geothermal Loop Experiment Facility.

reservoir in Imperial Valley in southern California. This development could not have occurred without the lessons learned at the cooperative government/industry Geothermal Loop Experimental Facility (GLEF) on handling brines that are eight times saltier than seawater. The development of the crystallizer/clarifier at this facility in the late 1970s effectively opened the estimated 2000 MW_e capacity of the area to economic use. A 34-MW_e dual-flash plant now stands on the site of the GLEF.

In recent years, the geothermal industry has made appreciable strides in locating and developing hydrothermal reservoirs; however, the lack of techniques to locate and characterize fractures in underground rock formations significantly inhibits industry's ability to tap consistently the areas of greatest fluid productivity. As a result, many reservoirs have not reached full production potential because they cannot be sufficiently characterized to allow development of cost-effective exploitation strategies.

Effective techniques are similarly lacking for identifying hydrothermal systems in regions where shallow cool groundwater effectively masks the underlying heat. This is particularly important in the Cascade Mountain Range in the Pacific Northwest, where the presence of a very large hydrothermal resource is suspected.

Although injection of spent geothermal fluids back to the subsurface is practiced by virtually all power plant operations, industry is still fearful of the thermal "short circuit" — prematurely cooling the fluids in the production zone, which can be caused by insufficient knowledge of the best location for injection wells. Another problem is that removal of solids from spent fluids prior to injection creates large amounts of sludges that require disposal. Despite these problems, however, nearly all spent hydrothermal fluids must be injected underground to maintain the pressure of the reservoir, dispose of the fluids acceptably, and prevent potential land surface subsidence caused by the withdrawal of fluids.

Hydrothermal well costs have declined significantly at some geothermal fields; the most economical are estimated to be only one and a half times as expensive as those of oil and gas drilling. However, at other fields, well costs still constitute a major deterrent to increased development. For example, titanium drill pipe is being used at $1000/ft in the harsh Salton Sea environment.

Although large-scale binary cycle technology has been tested at a government/industry 45-MW_e plant, at this time the technology is marginally economic for commercial use. Further improvements in efficiency and cost-effective systems are needed to fully exploit the moderate-temperature reservoirs.

In the past decade, extensive research and field experience have identified and proven solutions to many of the adverse interactions between brine and energy extraction equipment and materials. There are now technically satisfactory and economical ways of managing almost all the problems that appeared intractable in the early 1970s. For example, the Department of Energy (DOE) program has supported development of more durable high-temperature elastomers and concretes, and brine studies have promoted understanding of the effects of troublesome compounds. However, because the remaining undesirable interactions differ greatly from reservoir to reservoir, methods to predict or detect them as they occur are needed, along with reductions in the cost of materials that will withstand them.

Geopressured Status

Long-term production tests have shown that geopressured reservoirs will produce more brine than conventional oil reservoir models would predict. Although this result is desirable, its causes are unknown. Some potential causes may result in eventual reservoir failure. The reservoir drive mechanisms are not yet understood sufficiently, and more confidence is needed in techniques for locating and evaluating geopressured reservoirs. However, one of the major obstacles to long-term geopressured production has been removed with the development of a successful scale inhibitor through a joint effort between industry and DOE. Scale formation, both downhole and on surface equipment, had impeded production during early flow tests of four "design wells" (wells drilled specifically for experimental geopressured production) and eight "wells of opportunity" (abandoned oil and gas wells). In addition, geopressured R&D has confirmed that the brines are saturated with methane of pipeline quality, which can be used for industrial or home heating or converted to fuels-for-mobility as compressed natural gas, liquefied natural gas (LNG), or methanol.

Hot Dry Rock Status

The hot dry rock (HDR) concept has been proven on a modest scale with a small, shallow (Phase I) reservoir, which produced up to 5 megawatts-thermal (MW_t). A much larger, deeper, and hotter reservoir (Phase II) has now been completed for testing. A long-term test will provide needed knowledge on the characteristics and limits of a hot dry rock reservoir. To bring this technology to a competitive stance, more cost-effective technologies are needed for creating and mapping heat exchange fractures and for drilling and completing HDR wells under high-temperature conditions. These technologies will allow the development of more economical HDR systems.

Magma Status

The scientific feasibility of extracting energy from molten rock has been proven by DOE experiments at a shallow, encrusted lava lake in Hawaii. However, the scientific and engineering technology to locate subsurface magma chambers and to extract energy from them has yet to be developed and tested. The economic feasibility of magma energy will depend primarily on the availability of the resource, the cost and lifetime of energy extraction wells, and the effectiveness of downhole heat exchange processes.

Program Overview

The status of the technologies for exploiting all forms of geothermal energy indicates that technology improvements are needed before the more difficult resources — moderate-temperature hydrothermal fluids, geopressured brines, hot dry rock, and magma — can compete economically with conventional power generation technologies. Until these technologies become available for industry use, this resource cannot meet its full potential in the nation's energy supply mix. Providing support for technology development and transfer through government/industry cooperation is the focus of the DOE Geothermal Energy R&D Program. Its priorities are governed by those research paths, which appear to hold promise for future economic expansion of geothermal development and use.

Program Objectives

Three levels of quantitative programmatic objectives are defined in the 1988-1992 multiyear plan of the DOE Geothermal Energy R&D Program. Level I objectives, identified in Exhibit 3, address reductions in the life-cycle costs of energy from geothermal power production projects (e.g., a binary power plant including its geothermal fluid supply).

Exhibit 3
Level I Objectives for the Geothermal Program

(Energy cost target range is expressed as levelized in 1986 constant dollars.)

- Reduce the life-cycle cost of producing electricity with liquid-dominated, moderate-temperature 150°-200°C (300°-400°F) hydrothermal fluids to 3¢-10¢/kWh by 1992. (This compares with a cost range of 4¢-18¢/kWh for hydrothermal electricity as of 1986.)
- Improve geopressured technology to the point where electricity could be produced commercially in a cost range of 6¢-10¢/kWh by 1995.
- Provide hot dry rock technology such that electricity could be produced commercially from hot dry rock sites in a cost range of 5¢-8¢/kWh by 1997.
- Develop magma technology to the point where electricity could be produced experimentally from magma in a cost range of 10¢-20¢/kWh by the year 2000.

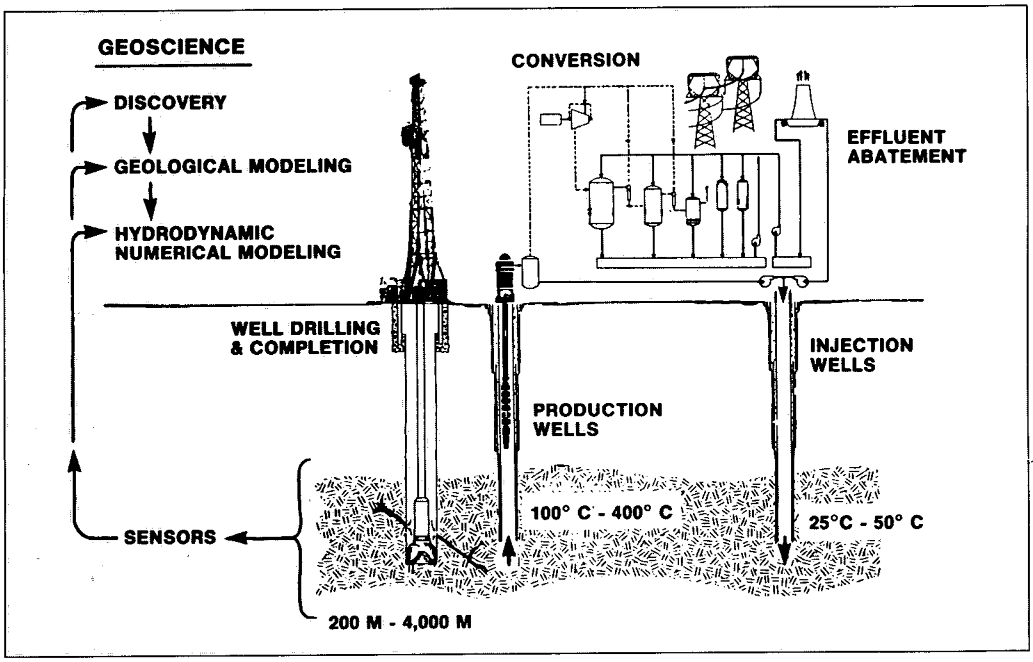


Figure 5. Geothermal power project components.

Level II objectives indicate how much improvement is expected to occur within major power project components as a result of federally funded research. In this way, the degree to which improvements in each component — e.g., fluid production — will contribute to reductions in the total cost of a project can be determined. Level III objectives prescribe the technical direction of each research project and provide the technical yardstick by which progress can be measured. For example, a Level II objective to improve the accuracy of siting geothermal wells will drive a Level III research project to develop the technology needed to bring about such improvement. Before a project is considered for funding, a preliminary estimate is made of its potential impact at all three levels. Typical geothermal power project components are illustrated in Figure 5.

Industry is actively participating in the planning and implementation of the program objectives. Its response to the results of objective achievement — i.e., whether industry's development planning and activities extend to more difficult geothermal resources in the 1990s and beyond — will be the final test of the effectiveness of DOE's geothermal research.

Technology transfer is an integral part of the geothermal program, and industry participation in program activities is the most direct avenue for the transfer.

Program Structure

The program's R&D is structured around the four resource categories of geothermal energy. Each category in turn embraces several projects:

- Hydrothermal
  - — Reservoir Technology
  - — Hard Rock Penetration
  - — Conversion Technology
- Geopressured
  - — Well Operations
  - — Geosciences and Engineering Support
  - — Energy Conversion
- Hot Dry Rock
  - — Fenton Hill Operations
  - — Scientific and Engineering Support

- Magma
  - — Long Valley Operations
  - — Laboratory and Engineering Support.

In the following section, only hydrothermal is discussed at the task (or third-tier) level; the other three resource categories are discussed only at the project (second-tier) level, because their research activities are not broken down to as great an extent.

FY 1988 Program Activities

Hydrothermal

Reservoir Technology

The reservoir technology project embraces five tasks:

- Reservoir Analysis
- Exploration Technology
- Brine Injection
- Geothermal Technology Organization
- Salton Sea Scientific Drilling.

The major areas of research interest, the research performed, and the significant accomplishments of each of these tasks in FY 1988 are as follows:

- **Reservoir Analysis** — In FY 1988, the emphasis of this task was on methods to replace costly drilling as the only means of providing evidence that a reservoir is adequate to support power generation for the expected life of a proposed plant. Such evidence is essential if investment capital is to be forthcoming. The research centered on refinements of geoscience techniques for locating fracture zones and permeable formations, methods for predicting producibility and longevity of reservoirs, analysis of data from producing fields, and verification of reservoir models. Significant accomplishments included 1) numerical codes to calculate the electromagnetic response caused by thin fracture zones of arbitrary orientation and dimensions, and 2) applied vertical seismic profiling techniques to map fracture orientations at The Geysers and Salton Sea geothermal fields. The numerical codes and seismic profiling techniques are important tools in resource characterization with a reduced number of wells — i.e., they permit the field operator to relate information gained from one well — rather than multiple wells — to the field around it.

- **Exploration Technology** — The exploration task is designed to develop techniques to locate and characterize geothermal resources in young siliceous volcanic environments, particularly in areas with deep circulation of groundwater. Geological, geophysical, and geochemical data have been acquired by cost-sharing with industry the drilling of several deep heat flow holes in the Cascade Mountain Range of the Pacific Northwest and will be integrated in reservoir models. Gathering of the field data was completed in FY 1988, leading to advancements in the use of deep heat flow holes as a tool to locate geothermal resources hidden by deep movement of groundwater in the Cascades.

- **Brine Injection** — The injection task focuses on techniques to predict the intensity and timing of the thermal, chemical, and hydrologic effects of injection. These prediction techniques will lead to methods for reducing temperature and pressure degradation in geothermal reservoirs. Three specific areas are addressed: fluid migration, fluid-rock chemical interactions, and injection well placement. Several major studies were completed in FY 1988, and reports were issued on nonisothermal injection testing and analysis, cooperative East Mesa field tests, and other related research. Other accomplishments included 1) models for the interpretation of injection tests in fractured reservoirs, 2) techniques to use tracer test results to design optimal injection schemes, and 3) a dual permeability model to simulate flow in fractured rock with secondary porosity. These are all techniques for maintaining reservoir pressure while avoiding thermal breakthrough to the producing zone.

- **Geothermal Technology Organization (GTO)** — The GTO is a new joint DOE/industry group formed to identify and support technology development efforts that have a high probability of yielding immediate benefits to the geothermal industry in the areas of reservoir performance and energy conversion. The emphasis is on products or services that can be commercialized after project completion. Each project will be jointly funded by DOE and participating industry partners with industry providing at least 50% of the total cost. The organization began one project in FY 1988 — a microseismic study of The Geysers geothermal field. GEO Operator Corp. and the Unocal Geothermal Division are the industry participants.

  The GTO and the Geothermal Drilling Organization (GDO), discussed below, are major technology transfer mechanisms. Industry takes the lead in identifying priority projects, and is thus involved with the technology development from the outset. Industry operations frequently serve as the test site for new technology and methods.

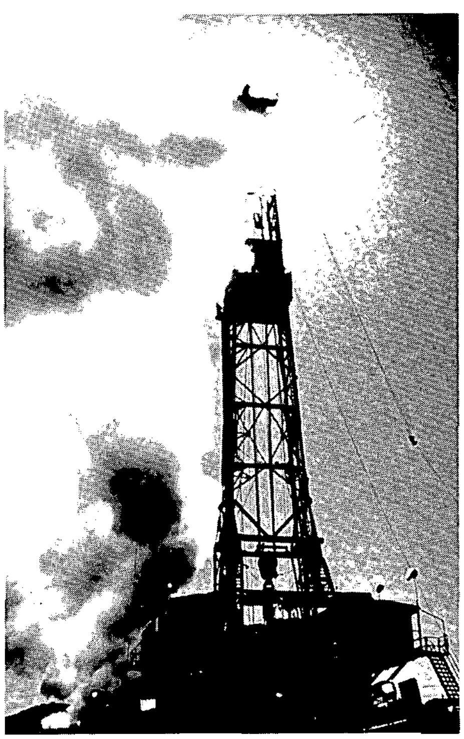
- **Salton Sea Scientific Drilling Task** — FY 1988 was another active year at the 10,560-ft well that comprises the Salton Sea Scientific Drilling Task. This well was drilled to better define the Salton Sea hydrothermal system, to test for extension of the system to greater depths, and to obtain unique scientific data. In FY 1988, the testing facility was reconditioned, and a successful 20-day production flow test was conducted, with flow rates up to 700,000 lb/h of hot 260°C (500°F) brine. Ancillary studies of brine chemistry, waste disposal, and microseismic detection were also carried out.

Hard Rock Penetration

The hard rock penetration project consists of four tasks:

- Lost Circulation Control
- Rock Penetration Mechanics
- Instrumentation
- Geothermal Drilling Organization.

The function of these combined tasks is to develop technology for geothermal drilling and well completion that will result in a significant reduction in the cost of geothermal wells. These costs are still 1.5 to 4 times the cost of oil and gas wells because of the hostile geothermal environment of high



Drilling at The Geysers Geothermal Complex.

temperatures, hard rock, and highly corrosive fluids. Realization of lower costs will result in expansion of the economic geothermal resource base.

- **Lost Circulation Control** — By industry consensus, loss of circulation in the drilling fluid system is the most costly aspect of geothermal drilling because of the time and expense involved in reestablishing circulation. In FY 1988, R&D was undertaken to develop a basic understanding of the two-phase (solid/liquid) flow phenomenon that dictates fracture plugging mechanics for single-particle, high-temperature, and multiple-constituent lost circulation materials. In addition, the plugging characteristics of high-temperature lost circulation materials were measured under a range of temperature and pressure conditions. Major accomplishments included 1) a mathematical model of the particle bridging process, which is the first step in plugging a lost circulation zone; and 2) a well site system for acquiring data required for transient hydraulic analysis during lost circulation.

- **Rock Penetration Mechanics** — Research in rock penetration mechanics is directed at reducing rock penetration costs by improving drilling/coring systems. Activities during FY 1988 included the development of a concept for a core drilling system for deep thermal regimes, and working with industry suppliers, the completion of two designs for insulated drill pipe, which will mitigate problems inherent in drilling in high-temperature regimes.

  Also in 1988, analysis of acoustical data telemetry through the drill string was completed, and testing of a laboratory scale model of the drill string transmission system showed excellent agreement between theory and lab data. Telemetry of data collected at the drill bit while drilling can significantly reduce well costs and increase production by increasing the rate at which downhole information is received and interpreted at the surface.

- **Instrumentation** — The research performed under this project in FY 1988 was cost-shared with industry to bring new technology to a point where industry/government joint projects can be identified for final development. A User Group was formed to promote the use and further development of a computer code to calculate the forces on a bit and bottom-hole assembly that will permit optimization of well design. Also during FY 1988, a new lower power transmitter was fabricated and added to a prototype radar fracture mapping tool, shown in Figure 6. The tool is being developed to locate fractures in a rock formation that do not intersect the wellbore. Field tests in FY 1988 showed that it can detect distinct targets in nonuniform geologic media.

FAR WELLBORE FRACTURE MAPPING SYSTEM

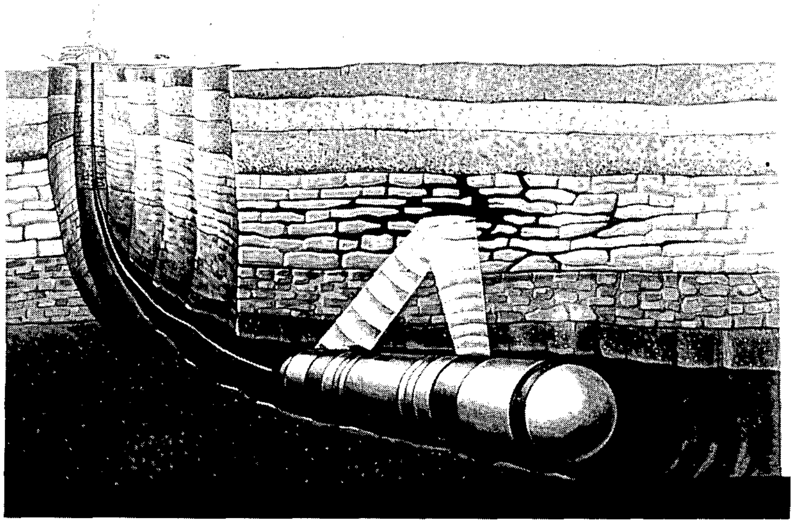


Figure 6. Instrumentation designed to locate fluid-filled fractures in the rock.

- **Geothermal Drilling Organization** — The GDO serves as a vehicle to respond to industry priorities in exploiting the commercial potential of research technology. Its function is very similar to that of the GTO, except that it concentrates on the transfer of drilling technology. Industry shares at least 50% of all project costs. In 1988, a high-temperature borehole televiewer was assembled and successfully demonstrated in a hot well owned by Unocal in Long Valley, Calif. The televiewer is being developed for casing inspection and fracture mapping in the open wellbore. A test of a tool for deploying an expanding foam in lost circulation zones at The Geysers showed insufficient expansion of one type of foam under field conditions. In addition, three field tests of a downhole air turbine for directionally drilling geothermal wells were completed at The Geysers. The tests gave promising results and led to design modifications of the transmission assembly. Temperature-resistant elastomer materials, needed to protect and prolong the life of drilling system components, were screened for suitability for use in the fabrication of drill pipe protectors.

Conversion Technology

The conversion technology project embraces three tasks:

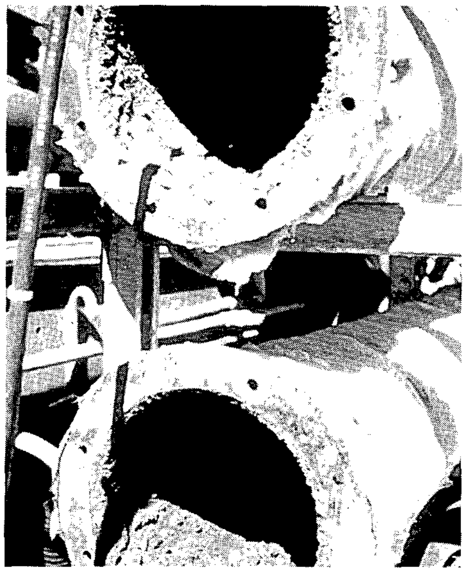
- Heat Cycle Research
- Materials Development
- Advanced Brine Chemistry.

- **Heat Cycle Research** — The heat cycle R&D focuses on improving the performance of binary cycle technology to levels approaching the maximum practicable thermodynamic efficiency. The purpose of this effort is to develop advanced systems that will extend the economics of commercial geothermal power generation to the more abundant, lower quality reservoirs where temperatures are not suitable for flash steam technology.

  A major tool in the heat cycle research is the Heat Cycle Research Facility (HCRF), a 50-kW_e binary cycle unit, in which supercritical cycle tests are conducted involving mixed working fluids, variations in condenser attitude, and supersaturated turbine expansion. In FY 1988, testing was completed with the condenser at the near vertical position with the propane family of working fluids. Phase I of the relocation of the HCRF from the Geothermal Test Facility at East Mesa, Calif., to the property of the nearby B. C. McCabe binary plant was also completed. The second phase of the relocation was initiated, including installation of a two-dimensional expansion nozzle and a reaction turbine and the necessary modifications to allow for testing of this equipment. Geothermal researchers completed an analysis of the application of the new Kalina concept to geothermal power cycles, and evaluated data from previous experiments with a near horizontal condenser.

- **Materials Development** — Under this project, R&D is aimed at developing, for use by the geothermal industry, technologically viable materials that can withstand still higher temperatures and more chemically aggressive reservoirs than are economically available today. Major 1988 activities included downhole testing of advanced high-temperature 300°C (572°F) lightweight cements for well completions, which produced very promising results; initial steps for conducting tests of polymer-lined heat exchanger tubing; and completion of an analysis of high-temperature elastomers for use in geothermal sealing applications.

- **Advanced Brine Chemistry** — Two distinct approaches address the expensive operating problems associated with brine chemistry. First, numerical modeling of complex brines will allow improved prediction of the thermodynamic conditions under which problems will occur in geothermal power plants from scale deposition, corrosion, and


Scaling on pipe is avoided by knowledge of brine chemistry.

suspended solids. The second approach is to monitor brine flow lines to detect these problems before they result in plant failure. In 1988, the interim brine equilibrium model for silica, calcite, and carbon dioxide was completed; the model will now be expanded to additional minerals in order to make it a more realistic simulator. In addition, laboratory tests of prototype particle meters were conducted using a high-temperature, high-pressure synthetic brine so that technical problems experienced in field tests could be corrected. An ultrasonic particle meter was tested at the Salton Sea Scientific Drilling Project to learn how the instrument would perform under actual field conditions; a report on its performance is forthcoming.

Other research conducted under the brine chemistry task is the series of experiments under way on the use of a biochemical technique to concentrate and remove toxic metals from wastes: the leaching of metals by micro-organisms from sludge-like residues that result from the precipitation of minerals from spent geothermal brines before they are injected back into the ground. This process is applicable in situations where toxic heavy metals are present in large volumes of solid geothermal waste at concentrations too high for conventional disposal methods.

Geopressured-Geothermal

Well Operations

The well operations project involves field activities to obtain information on reservoir performance under production conditions, surface handling systems, disposal well injection procedures, brine chemistry and scale inhibitor treatment, and automation. Two Gulf Coast geopressured-geothermal design wells are being subjected to reservoir performance tests, and a former deep gas well, donated to DOE by the Superior Oil Company, is also under consideration for performance testing.

The Pleasant Bayou well, one of the design wells, is located in Brazoria County, Tex., near Houston. It is completed into a geopressured aquifer extending from 14,620 to 14,740 ft. The brine temperature is about 150°C (300°F) with a salinity of 130,000 mg/L. Utilizing current separation technology, about 22 scf/bbl of natural gas can be recovered. The well was placed back in production in May 1988, after being treated with a scale inhibitor, and has been flowing at about 20,000 bbl/d, a very high brine production rate.

The other design well, the Gladys McCall, is located in Cameron Parish, La., and is completed in the 15,160 to 15,470 ft interval. The brine temperature is 145°C (293°F). This well was subjected periodically to high rate flow tests at over 25,000 bbl/d of brine for more than two years. It produced a total of more than 27 Mbbl of brine and nearly 676 Mscf of methane, and was the subject of the breakthrough in geopressured scale inhibition treatment. It was shut in during October 1987, and is undergoing a long-term pressure build-up test to help in understanding the drive mechanisms of geopressured reservoirs. This will result in improved predictions of reservoir performance and enable better estimates of economic viability.

The Willis Hulin well was drilled in Vermilion Parish, La., as a commercial gas producer. It penetrated an unusually good geopressured zone at about 20,000 ft, and when it was no longer operable as a gas well, DOE agreed to assume ownership. Most of the physical parameters of the Hulin well differ from those of the design wells, and it thus provides the opportunity to facilitate determination of drive mechanisms under another set of downhole conditions. In addition, the higher expected temperature and gas content make fluid from the Hulin well substantially more valuable per unit volume than fluid from the design wells. Thus, the well presents a unique opportunity to acquire valuable data at a much lower cost than comparable data from a new well. During FY 1988, annular pressures at the wellhead were monitored on a regular basis, site facilities were upgraded in preparation for workover activities, and a safety evaluation of well pressure buildup was performed.

Geoscience and Engineering Support

Geopressured geoscience and engineering support is focused on analyzing geopressured well data and understanding how geopressured-geothermal reservoirs respond to long-term, high-volume production. Reservoir analysis and the continuing refinement of the reservoir model previously developed by DOE will determine reservoir characteristics and drive mechanisms and ultimately allow the prediction of long-term production on the basis of short-term tests. Geological studies will help to delineate reservoir size and volume, information necessary for an accurate reservoir model. Deformation of the reservoir rock samples under in situ stresses in the laboratory will yield rock mechanics data also necessary for the reservoir model. Accurate interpretation of logs is necessary for acquiring basic information such as salinity and porosity. Researchers are examining the effects of rock stress, shale content, and wettability on rock resistivity, and the effects of trace elements on neutron logs. The variation with time of organic chemicals produced with the brine is being measured. Environmental monitoring at the geopressured well sites and archiving of geopressured data and reports is continuing.

FY 1988 accomplishments of this project included 1) refined mapping of Pleasant Bayou reservoir sandstone within the fault block; 2) development of simplified geologic models; 3) continued analysis and interpretation of the multirate flow tests of the Gladys McCall as well as shut-in data starting in October 1987 (the first downhole data after the reservoir started to recover); and 4) conclusion that environmental monitoring at the Gladys McCall has not shown any detrimental environmental effects attributable to the long-term testing (microseismic, water quality, and subsidence).

Energy Conversion

The methane, high pressures, and heat of geopressured brines can be used to produce electric power; conversely, the methane can be sold to a pipeline and the energy used directly or to produce electricity or mobility fuels. If both methane and heat are used for electricity production in the same system, waste heat from the burning of methane can be transferred to a binary fluid for increased energy efficiency. Such "hybrid" power systems produce more electricity than the same amount of gas and geothermal heat used in separate power plants. The construction of a "hybrid" conversion system was begun in FY 1988 at the Pleasant Bayou well site, and a power generation experiment is planned. In FY 1988, flow testing of the well resumed in preparation for the experiment, and construction of the power system began.

Hot Dry Rock

Fenton Hill Operations

The focus of the Fenton Hill Operations Project in FY 1988 was on preparing for the upcoming Long-Term Flow Test (LTFT) of the Phase II reservoir. This test is a significant milestone in hot dry rock research because of the information it will provide on reservoir impedance, thermal drawdown, energy output, and water consumption. The significant FY 1988 accomplishment was completion of the repair of the well used to produce heated water from the man-made reservoir. The repair was accomplished by redrilling into the existing reservoir and sidetracking the well around the damaged section. This work will enable full-flow production during the LTFT of the reservoir. Also in 1988, components for the surface system for the LTFT were procured, and work continued on installing the system. The hot dry rock concept is illustrated in Figure 7.

Scientific and Engineering Support

This project is focused on providing the support needed to meet HDR objectives during the LTFT such as formulating, verifying, and iterating as necessary the thermal/fluid dynamic modeling of the reservoir; planning and directing downhole experiments; analyzing acquired data; and verifying reservoir performance.

The project provides downhole instruments and equipment for use in the reservoir through upgrading/modifying existing downhole tools, or, when

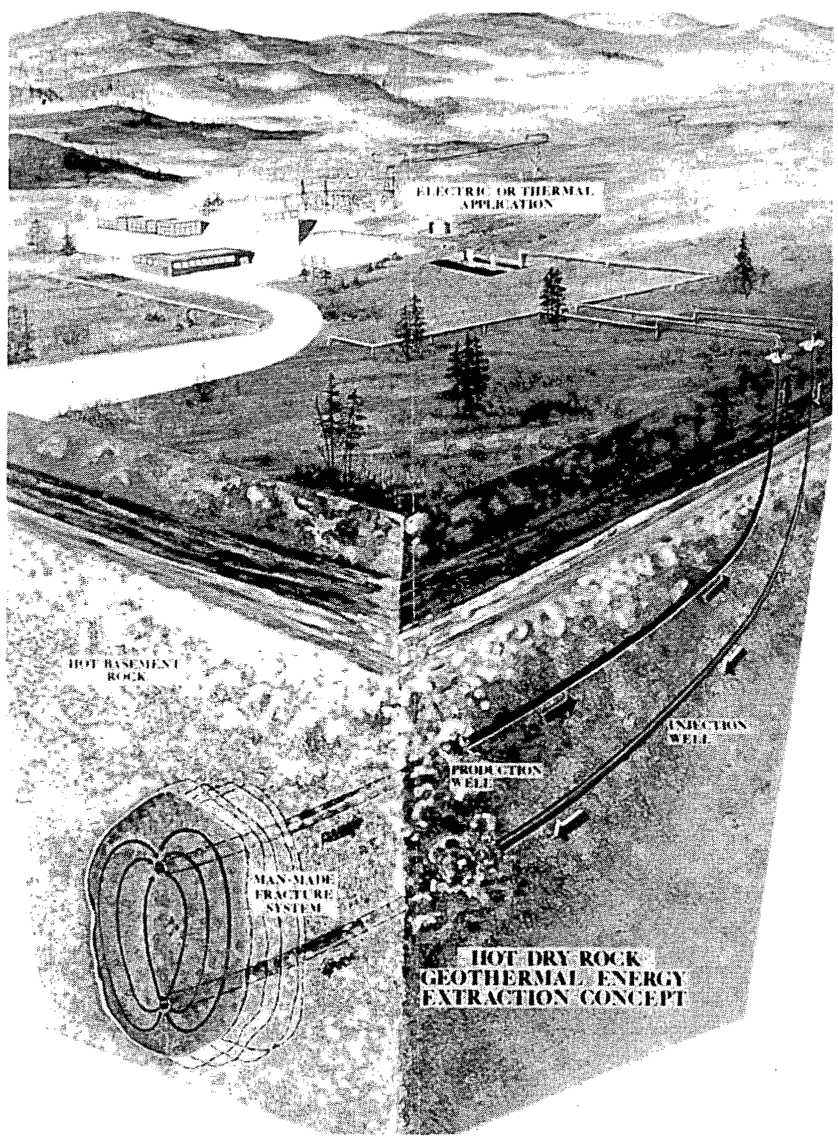


Figure 7. Hot dry rock concept.

necessary, developing new ones. Reservoir microseismic analysis and development of techniques to estimate reservoir size and productivity are also among the responsibilities of this task. FY 1988 accomplishments included a re-analysis of the micro-earthquakes resulting from the massive hydraulic fracturing experiment of 1983 using improved mapping methods and initiation of a programming effort toward automation. A prototype borehole televiewer was also completed, and the injection borehole was surveyed.

Magma

Long Valley Operations

Large silicic volcanic systems contribute significantly to the estimated total geothermal resource base. To evaluate the availability of crustal magma resources in these systems and to test the adequacy of current geophysical techniques for locating magma, an exploratory well will be drilled at Long Valley, Calif.

The key achievement of this project in FY 1988 was selecting an exploratory drill site in the Long Valley caldera, which was approved by a DOE review panel. This selection is supported by extensive geophysical analysis. Figure 8 is a simplified depiction of the results of this analysis. Permits for operation at the site were initiated, and preliminary site work was completed. A science guide for supporting scientific measurements in the exploratory well was developed during a workshop attended by more than 60 researchers.

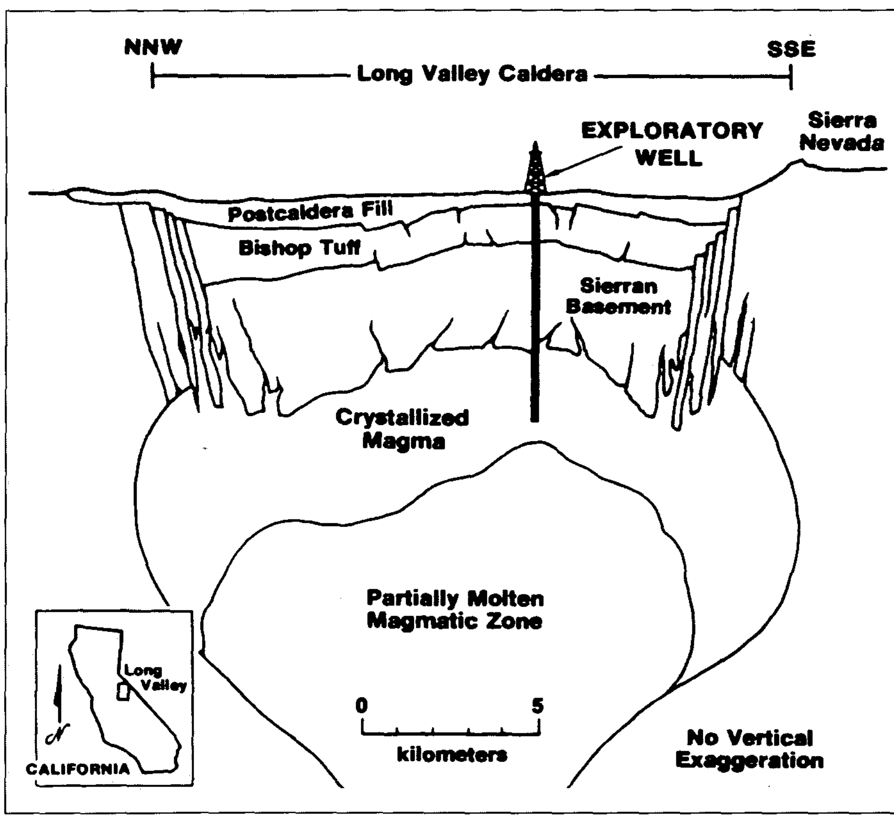


Figure 8. Subsurface view of Long Valley Caldera as depicted by geoscientific studies.

Laboratory and Engineering Support

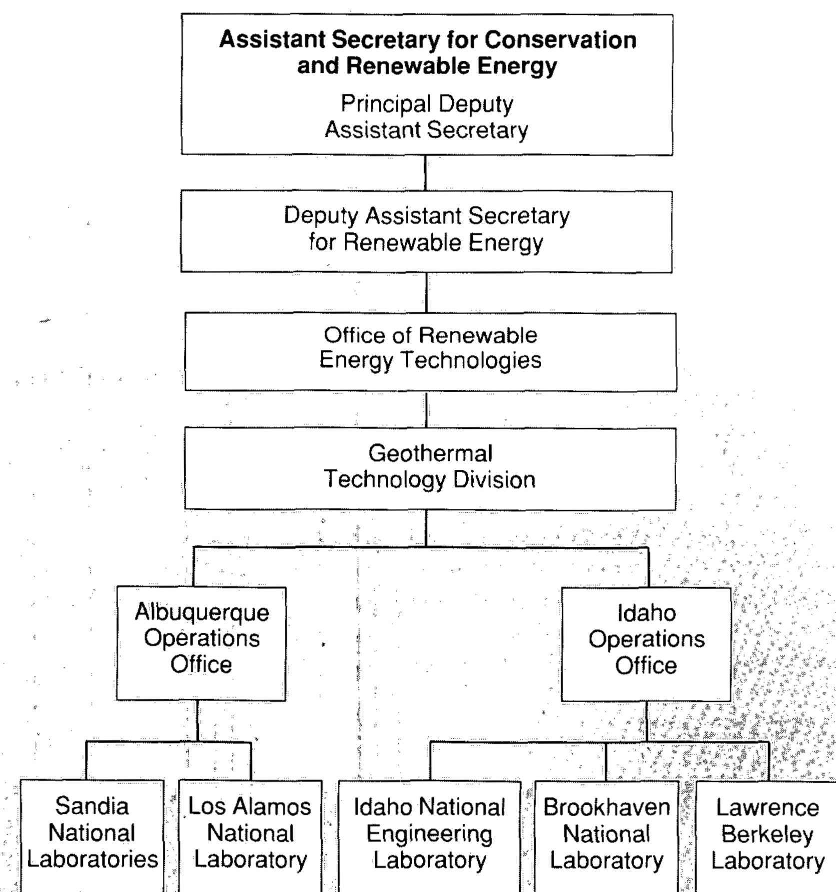
In FY 1988, research continued in the energy extraction and geochemistry/materials tasks. Advances were made in evaluating magma convection, overall energy extraction analysis, analysis of energy conversion systems, understanding thermal fracturing processes, examining the reaction of potential heat exchanger materials with magmatic fluids, evaluating mass transport near the heat exchanger, and collecting laboratory data related to potential hazards during drilling.

Program Management

Organization

The Geothermal Program is managed by the director of the Geothermal Technology Division (GTD) at DOE Headquarters, Washington, D.C. GTD is responsible to the DOE Assistant Secretary for Conservation and Renewable Energy, through the Director, Office of Renewable Energy Technologies and the Deputy Assistant Secretary for Renewable Energy, as shown in Exhibit 4.

Exhibit 4
Geothermal R&D Program Participants



The headquarters organization provides the centralized leadership necessary to ensure that program activities are consistent with national energy policy, priorities, and directives. Management of technical activities is decentralized among DOE field offices and national laboratories to ensure that specialized technical expertise is available to supervise the research.

To ensure the continuing exchange of technical and programmatic concerns, the division sponsors an annual program review during which the operations offices, national laboratories, universities, and industry contractors provide updates on their activities. This review is open, and the public is encouraged to attend. Twice a year, the participants in each research category gather for a program review to report on category-specific activities. At Headquarters, the director holds monthly informal conferences where program managers report on current technical and programmatic issues and problems in their respective areas.

Budget

The FY 1988 geothermal R&D budget is summarized in Exhibit 5.

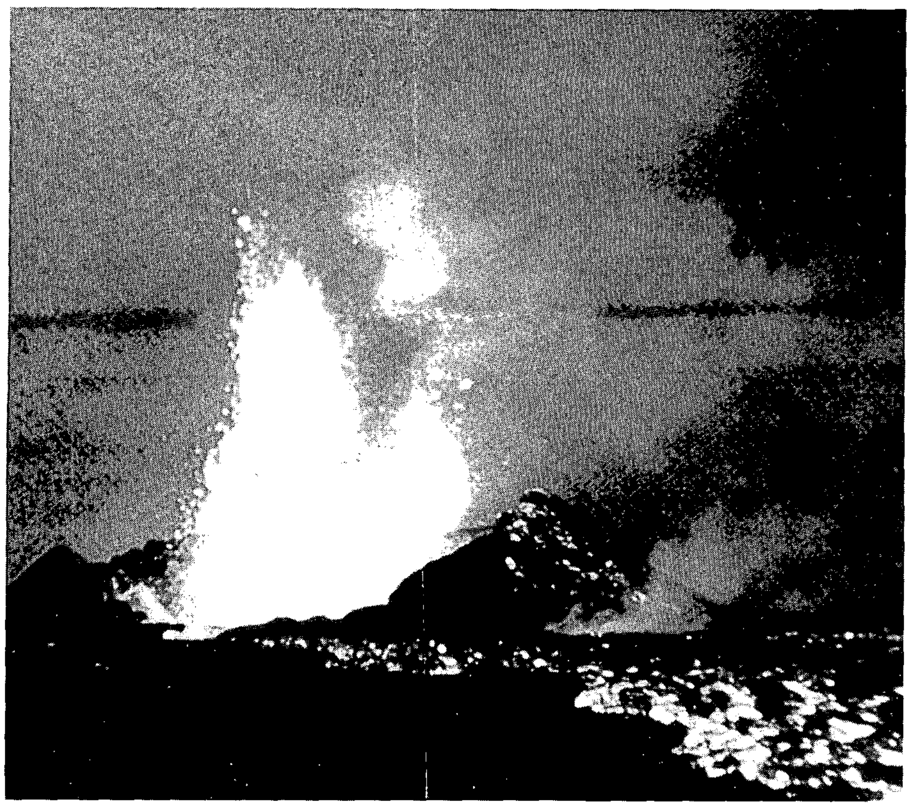
Exhibit 5
FY 1988 Geothermal Program Budget

Activity	Operating Budget ($000)
Hydrothermal	$7,785
Geopressured	4,955
Hot Dry Rock	5,770
Magma	1,380
Capital Equipment	0
Program Direction	835
Total, Geothermal Technology	**$20,725**

The Outcome

Geothermal energy is a here-and-now technology for use with dry steam resources and high-quality hydrothermal liquids. These resources are supplying about 6% of all electricity used in California. However, the competitiveness of power generation using lower quality hydrothermal fluids, geopressured brines, hot dry rock, and magma still depends on the technology improvements sought by the DOE Geothermal Energy R&D Program.

The successful outcome of the R&D initiatives will serve to benefit the U.S. public in a number of ways. First, if a substantial portion of our geothermal resources can be used economically, they will add a very large source of secure, indigenous energy to the nation's energy supply. In addition, geothermal plants can be brought on line quickly in case of a national energy emergency.



Geothermal energy is also a highly reliable resource, with very high plant availability. For example, new dry steam plants at The Geysers are operable over 99% of the time, and the small flash plant in Hawaii, only the second in the United States, has an availability factor of 98%. Geothermal plants also offer a viable baseload alternative to fossil and nuclear plants — they are on line 24 hours a day, unaffected by diurnal or seasonal variations.

The hydrothermal power plants with modern emission control technology have proved to have minimal environmental impact. The results to date with geopressured and hot dry rock resources suggest that they, too, can be operated so as to reduce environmental effects to well within the limits of acceptability. Preliminary studies on magma are also encouraging.

In summary, the character and potential of geothermal energy, together with the accomplishments of DOE's Geothermal R&D Program, ensure that this huge energy resource will play a major role in future U.S. energy markets.